

## PERIODIC PHOTOMETRIC VARIABILITY IN THE BECKLIN-NEUGEBAUER OBJECT

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Received 2000 September 1; accepted 2000 November 1; published 2001 January 18

### ABSTRACT

The Becklin-Neugebauer object (BN) in the Orion Nebula cluster is a well-studied, optically invisible, infrared-bright young stellar object that is thought to be an intermediate-mass protostar. We report here that BN exhibited nearly sinusoidal periodic variability at the near-infrared  $H$  and  $K_s$  bands during a 1 month observing campaign in 2000 March/April. The period was 8.28 days, and the peak-to-peak amplitude was  $\sim 0.2$  mag. Plausible mechanisms for producing the observed variability characteristics are explored.

*Subject headings:* infrared: stars — stars: individual (Orion BN/KL) — stars: pre-main-sequence — stars: variables: other

### 1. INTRODUCTION

The Becklin-Neugebauer object (BN) was revealed during early raster scanning of the Orion Nebula region at  $2\ \mu\text{m}$  and was immediately recognized as a candidate protostellar object (Becklin & Neugebauer 1967). BN is the brightest at near-infrared wavelengths of a group of  $\sim 20$  intermediate- and high-mass young stars and protostars in OMC-1. These objects were discovered at mid-infrared (Rieke, Low, & Kleinmann 1973; Downes et al. 1981; Lonsdale et al. 1982; Dougados et al. 1993; Gezari, Backman, & Werner 1998), radio (Churchwell et al. 1987; Felli et al. 1993; Menten & Reid 1995), and X-ray (Garmire et al. 2000) wavelengths. The total luminosity emanating from the embedded cluster is  $\sim 10^5 L_\odot$ . In addition to its luminous point sources, the region is also notable as the source of the spectacular  $\text{H}_2$  “fingers” or “bullets” (Allen & Burton 1993) that extend several arcminutes to the northwest and southeast.

BN itself is extinguished by  $A_V = 17$  mag and has luminosity of  $2500 L_\odot$  (Gezari et al. 1998) corresponding to a main-sequence B3–B4 star. It was the first of a still small class of young, mostly luminous stars with the  $2\ \mu\text{m}$  CO band heads in emission (Scoville et al. 1979, 1983). These  $\Delta\nu = 2$  transitions are thought to arise from a collisional or shock excitation in a hot, dense region, perhaps the inner part of a circumstellar disk or wind. BN also has relatively strong  $\text{H}_2$  (Scoville et al. 1983) and weak  $\text{H}\alpha$ ,  $\text{P}\alpha$ , and  $\text{Br}$  hydrogen recombination lines (e.g., Bunn, Hoare, & Drew 1995). Broad absorptions at  $3.3$  and  $10\ \mu\text{m}$  are due to circumstellar ice and dust (Gillett & Forrest 1973).

### 2. PHOTOMETRIC MONITORING OBSERVATIONS

Time series photometry at  $J$ ,  $H$ , and  $K_s$  was acquired using the 2 Micron All-Sky Survey (2MASS) southern telescope at the Cerro Tololo Inter-American Observatory during gaps in right ascension that were not otherwise utilized when 2MASS was near completion. As described in Carpenter, Hillenbrand, & Skrutskie (2001, hereafter CHS01), 29 sets of photometry were obtained over an area less than  $\sim 0.84^\circ \times 6.0^\circ$  centered on the Trapezium region of the Orion Nebula cluster (ONC). Ob-

servations were conducted on nearly a nightly basis between 2000 March 4 and April 8 with BN observed on 28 of these nights. In addition to these specially scheduled observations, BN was observed twice during normal 2MASS operations on 1998 March 19 and 2000 February 6.

As detailed in the 2MASS Explanatory Supplement,<sup>1</sup> the image data consist of doubly correlated differences of two NICMOS readouts separated by the 1.3 s frame integration time. The first readout occurs 51 ms after reset and independently provides a short integration so as to recover unsaturated images of bright (5–9 mag) stars. Each position on the sky is observed 6 times in this manner as the telescope scans in declination. For BN, the photometric measurements at the  $K_s$  band are derived from the 51 ms integrations since the source saturates in the 1.3 s images. Magnitudes are obtained using aperture photometry with an aperture radius of  $4''$  and a sky annulus extending radially from  $24''$  to  $30''$ . The final magnitude is the mean of the six aperture magnitudes, and the photometric uncertainty is the standard deviation of the mean of the six measurements. At the  $H$  band, BN is faint enough that the magnitudes normally would be estimated with point-spread function (PSF) fitting on the 1.3 s images. However, since BN is located on an extended plateau of bright nebulosity, the PSF fit converged for only one of the 28 sets of observations. Therefore, we report aperture magnitudes at the  $H$  band as well, computed with an aperture radius of  $4''$  and a sky annulus extending radially from  $14''$  to  $20''$ . BN was not measured reliably at the  $J$  band.

Except for the time series aspect, the data set, as produced by IPAC, is identical in format to that produced for 2MASS itself, containing position, photometry, photometry error, and photometric quality flags. To improve the photometric accuracy within the time series data, a grid of bright, isolated stars with low night-to-night variations was defined over the full  $\sim 0.84^\circ \times 6.0^\circ$  survey region and used as internal standards in order to adjust the nominal 2MASS calibration zero points on a nightly basis. Typical zero-point corrections were less than

<sup>1</sup> See the Explanatory Supplement to the 2MASS Second Incremental Data Release of 2000 March by R. M. Cutri et al. (<http://www.ipac.caltech.edu/2mass/releases/docs.html>).

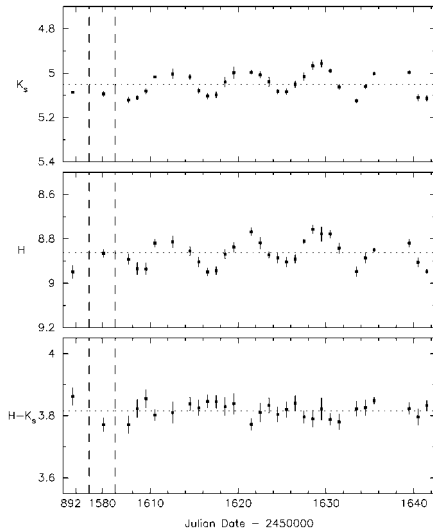


FIG. 1.—Light curves in the  $K_s$  band,  $H$  band, and  $H-K_s$  color for BN as seen by the 2MASS southern telescope in 2000 March/April. The dotted line is the mean magnitude over this time interval. The first two data points were taken during normal 2MASS operations and are disjoint from the rest of the data stream.

0.015 mag. The details of this procedure and all other processing and analysis steps are described in CHS01.

### 3. VARIABILITY CHARACTERISTICS OF BN

For all of our  $\sim 18,000$  point sources, we looked for photometric variability by comparing the observed brightness changes in time with those expected according to the formal photometric uncertainties. To quantify the likelihood that variability occurred within the time span of the observations, we employed both a  $\chi^2$  technique and a method developed by Welch & Stetson (1993) and Stetson (1996) that looks for correlated variability between multiple photometric bands.

The BN measurements exhibited  $\chi^2(K_s) = 21$ ,  $\chi^2(H) = 13$ , and a Stetson- $J$  variability index of 3.1 (where we have considered values of  $\chi^2 > 1.5$  and Stetson- $J > 0.55$  in CHS01 in order to identify variables). Light curves are shown in Figure 1 and the data are tabulated in Table 1. The error-weighted rms of the measurements, which are proportional to the variability amplitudes, were 0.06 mag at  $H$  and 0.04 mag at  $K_s$  compared with typical photometric uncertainties of less than 0.02 mag. The observed peak-to-peak amplitudes, neglecting errors in the photometry, were 0.26 at  $H$ , 0.17 at  $K_s$ , and 0.13 at  $H-K_s$ . The mean magnitudes were  $H = 8.87$  and  $K_s = 5.04$ .

BN's light curve is clearly periodic, and application of the Lomb-Scargle algorithm from Press et al. (1992) yields a period of 8.28 days at both  $H$  and  $K_s$  (analyzed separately) with false-alarm probabilities (FAPs) of less than 0.1%. The error in this period, according to the Kovacs (1981) formula for frequency shifts in Fourier analyses, is 0.05 days. We show the periodograms in Figure 2 and the phased light curves in Figure 3. The  $H-K_s$  color may also be periodic with the same oscillation as the  $H$  and  $K_s$  fluxes; however, this period is not significant (FAP = 38%). Color variations are such that  $H-K_s$  is redder when the star is fainter, in the proportions expected from a standard extinction law.

Returning to Figure 1, in addition to the periodicity, there is a brightening of the magnitudes by  $\sim 0.1$  mag at  $H$  and

TABLE 1  
TIME SERIES PHOTOMETRY FOR BN

Julian Date	$H$ (mag)	$K_s$ (mag)	Error ( $H$ ) (mag)	Error ( $K_s$ ) (mag)
2,450,891.509 .....	8.949	5.087	0.028	0.004
2,451,580.546 .....	8.865	5.094	0.018	0.011
2,451,607.526 .....	8.892	5.121	0.023	0.014
2,451,608.520 .....	8.934	5.111	0.027	0.010
2,451,609.520 .....	8.936	5.081	0.026	0.012
2,451,610.519 .....	8.819	5.017	0.017	0.003
2,451,612.553 .....	8.813	5.003	0.027	0.021
2,451,614.516 .....	8.855	5.017	0.019	0.010
2,451,615.515 .....	8.904	5.079	0.022	0.012
2,451,616.514 .....	8.949	5.103	0.017	0.012
2,451,617.514 .....	8.943	5.098	0.017	0.013
2,451,618.513 .....	8.869	5.040	0.020	0.021
2,451,619.511 .....	8.837	4.998	0.021	0.025
2,451,621.510 .....	8.768	4.996	0.017	0.009
2,451,622.512 .....	8.818	5.008	0.026	0.014
2,451,623.509 .....	8.872	5.039	0.014	0.020
2,451,624.507 .....	8.886	5.082	0.022	0.010
2,451,625.507 .....	8.904	5.084	0.021	0.013
2,451,626.506 .....	8.891	5.051	0.019	0.014
2,451,627.505 .....	8.811	5.015	0.010	0.017
2,451,628.499 .....	8.757	4.967	0.020	0.018
2,451,629.498 .....	8.778	4.956	0.032	0.016
2,451,630.498 .....	8.778	4.990	0.017	0.009
2,451,631.497 .....	8.842	5.062	0.022	0.011
2,451,633.491 .....	8.947	5.125	0.022	0.009
2,451,634.490 .....	8.886	5.060	0.022	0.011
2,451,635.489 .....	8.850	5.002	0.009	0.007
2,451,639.485 .....	8.819	4.996	0.017	0.007
2,451,640.480 .....	8.906	5.110	0.020	0.015
2,451,641.479 .....	8.947	5.114	0.009	0.013

$\sim 0.05$  mag at  $K_s$  over the first three cycles of the period; this brightening is more apparent once the sinusoidal behavior is subtracted. Yet the faintest point at the end of the third cycle and the last two points in the data stream at the end of the fourth cycle are all too faint to support the notion that this apparent rise is a long-term behavior pattern. Furthermore, the 2000 February and 1998 March flux levels indicate that this recent brightening trend originated not too much before the beginning of the 2000 March/April time series.

### 4. INTERPRETATION AND DISCUSSION

Given the protostellar nature of BN, it is worth considering the physical origin of the  $1.6\text{--}2.2\text{ }\mu\text{m}$  flux (the shortest wavelengths at which BN has been detected). Assuming the B3–B4

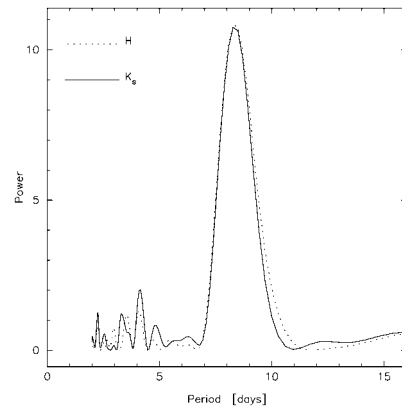


FIG. 2.—Periodogram for  $H$ - and  $K_s$ -band data. The most significant peak at 8.28 days has an FAP in the Lomb-Scargle formalism of less than 0.1%.

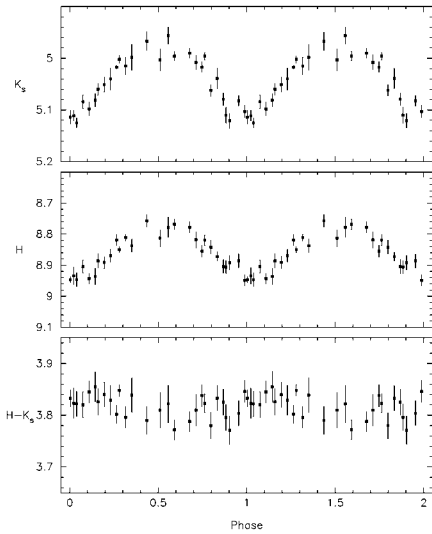


FIG. 3.— $K_s$ -band,  $H$ -band, and  $H-K_s$  light curves phased with a period of 8.28 days. Two full phases are shown.

spectral type and a visual extinction of 17 mag from Gezari et al. (1998), the  $H$ -band magnitude matches within a few tenths that predicted for a reddened stellar photosphere. We take this as minor evidence that the  $H$ -band photometric variability may arise close to the photosphere. At the  $K_s$  band, however, the (dereddened) magnitude is almost 4 mag above the predicted photosphere. The hot dust and/or gas producing the  $2.2\ \mu\text{m}$  excess must subtend an area larger than that predicted by a standard blackbody disk or shell model since all close-in grains are destroyed by stellar heating. Accretional heating is one way to do this. The fact that the  $K_s$ -band magnitude is dominated by circumstellar flux suggests, alternately, that the variability may occur in the dust envelope. Despite these differences between  $H$  and  $K_s$  in the ratio of nonphotospheric to photospheric flux, the observed periods are the same, with the ratio of period amplitudes consistent with reddening.

Periodic variable stars have been studied optically in the ONC region by Herbst et al. (2000 and references therein), Stassun et al. (1999), and Rebull (2001). Almost all stars identified as periodic in these unbiased studies have been low mass, i.e., less than  $2\ M_\odot$ . Only one periodic variable earlier than mid-G has been found, JW 660, with a mid-B spectral type and a mass of  $\sim 6\ M_\odot$  (Hillenbrand 1997). The period of 6.15 days reported by Mandel & Herbst (1991) has, perhaps notably, not been found again in subsequent observing seasons (Herbst et al. 2000). BN, by contrast, is a B3–B4 star with a mass of  $\sim 6\text{--}8\ M_\odot$  (and a maximum mass of  $20\ M_\odot$  if the B0 spectral type inferred from H II region characteristics is adopted). It is the most massive periodic variable detected thus far in the Orion region. The next brightest stars having significant periods in CHS01 are greater than 2.2 mag fainter at  $K_s$  with spectral types K0 and later.

BN's periodic variability could be due to a number of well-recognized phenomena, although none of the following explanations seems totally satisfactory. Periodic variability in young stars is usually interpreted in terms of long-lived nonuniformities in photospheric structure, i.e., spots that are either cooler or hotter than the stellar effective temperature. These spots rotate with the star and modulate the light curve as they pass through the line of sight of the observer. Interpreted as stellar rotation, the 8.28 day period implies an equatorial velocity of  $\sim 30\ \text{km s}^{-1}$  that is on the slow tail for rotation of intermediate-

and high-mass young stars in the ONC (S. C. Wolff, S. E. Strom, & L. A. Hillenbrand 2001, in preparation). It is not generally accepted that massive stars like BN have the surface magnetic structures required for the production of cool spots. However, given that BN is a protostar, hot spots could be produced in the presence of a magnetic dipole that channels material from an accretion disk along field lines to form surface shocks.

Considered independently, the variability amplitudes at  $H$  and  $K_s$  can be well modeled by spots with  $\Delta T \approx 15,000\ \text{K}$  from the photosphere and  $\sim 15\text{--}20\%$  coverage, or  $\Delta T \approx 5000\ \text{K}$  and  $\sim 50\%$  coverage, as examples. However, neither cool nor hot spots are capable of producing the small  $H-K_s$  color amplitude since the effect of adding a spot is essentially colorless in the near-infrared given the early-B photosphere ( $<0.02\ \text{mag}$  for  $\Delta T < 20,000\ \text{K}$  and  $<50\%$  coverage). If spot-modulated rotation is the cause of the observed photometric periodicity, both the phase and the amplitude should change on timescales of months to years as the spot structure varies. Although the 2000 February data point phases well with the period derived for the 2000 March/April time series, the 1998 March data point does not; however, this could simply be due to the accumulation of period error over the longer time baseline.

Pulsating behavior leads to short periods (0.1–0.3 days) in radial modes and to only slightly longer periods ( $<1\ \text{day}$ ) in nonradial modes (e.g.,  $\beta$  Cep stars in the early-B range and 53 Per-type stars and others at late B). Both the amplitude and the near-sinusoidal shape of BN's light curve are consistent with certain types of pulsational behavior, but the period is too long. Longer period variability ( $\sim 2\text{--}30\ \text{days}$ ) in massive stars is often explained in terms of winds, with some mechanisms requiring binary systems. The radio spectral index of BN is  $\alpha = 0.8 \pm 0.2$  from 2 to 6 cm (Felli et al. 1993), consistent with thermal emission from an ionized stellar wind.

The observed period and mass estimate for BN imply an orbital radius of  $\sim 0.15\ \text{AU}$  for any hypothetical low-mass companion. If an outflow/wind from a companion was colliding with the outflow/wind from BN, the pulsating behavior within the interaction region might be identified via X-rays (e.g., Ishibashi et al. 1999 for  $\eta\ \text{Car}$ ). BN was seen in heavily absorbed X-rays by Garmire et al. (2000) using *Chandra*.

Another scenario to consider is an eclipsing binary. BN's light curve does not seem consistent with a fully eclipsing system given its low amplitude and nearly sinusoidal nature. A partial eclipse situation with a near-equal mass/size companion, a small orbital separation ( $\sim 10R_*$ ), and a reasonable inclination ( $\sim 40^\circ$ ) would match the gross shape, period, and amplitude of the phased light curves. In the near-equal mass situation, the true orbital period would be double that derived naively from observations since a single revolution produces two minima and two maxima. However, eclipses should exhibit the same amplitude in all bands (modulo limb darkening), which is not what is observed for BN unless the companion has the same radius but the colors of a much cooler star. Interestingly, Scoville et al. (1983) and others have suggested the possibility of wide binarity for BN in order to explain its large radial velocity relative to other ONC stars and to the ambient cloud.

A further possibility is periodic occultation by asymmetry in a circumstellar disk at the 0.15 AU orbital radius implied by the period. High column density partially gray orbiting material could produce the shape of the light curve as well as the color and magnitude amplitudes. It is interesting in this context to note that Biscaya et al. (1997) claimed time variability in

TABLE 2  
HISTORICAL PHOTOMETRY FOR BN

Observation Date (UT)	Aperture Size (arcsec)	<i>H</i> (mag)	<i>K</i> (mag)	Error ( <i>H</i> ) (mag)	Error ( <i>K</i> ) (mag)	Reference
1965 Jan .....	13	9.8	5.2	?	?	1
1968 Sep 15 .....	?	9.19	4.88	0.10	0.07	2
1969 or earlier .....	?	9.60	4.87	?	?	3
1969 Dec 8 .....	?	8.57	4.72	0.15	0.15	2
1971 Mar 9 .....	15	8.48	4.5	0.13	?	4
1974 Sep 21 .....	7	9.45	4.76	0.10	0.10	2
1980 Feb .....	3.5	9.2	5.1	<0.3	<0.3	5
1981 Mar 14 .....	6	9.39	4.93	0.06	0.04	2
1982 or 1983 .....	4	...	5.5	...	<0.01	6
1988 Jan .....	6	9.8	5.4	0.1	0.1	7
1996 Nov/Dec .....	5.8	...	6.43	...	<0.2	8
1998 Mar 19 .....	8	8.95	5.09	0.03	<0.01	9
1999 Feb 9 .....	1.8	9.36	...	<0.01	...	10
2000 Mar/Apr .....	8	8.87	5.04	<0.03	<0.02	11

REFERENCES.—(1) Becklin & Neugebauer 1967; (2) G. Neugebauer 2000, private communication; (3) Low et al. 1970; (4) Penston 1973; (5) Lonsdale et al. 1982; (6) Hyland et al. 1984; (7) Minchin et al. 1991; (8) Simon, Close, & Beck 1999; (9) This Letter; (10) Hillenbrand & Carpenter 2000; and (11) This Letter, mean over time series.

BN's 2  $\mu\text{m}$  CO band head emission lines and that no emission is present in the spectrum of Penston, Allen, & Hyland (1971). The CO lines are formed in the dense, hot circumstellar environment, and their time variability may have the same physical origin as the continuum variability found by us.

Finally, we note that there may be historical precedent for photometric variability in BN, as detailed in Table 2. However, one must be cautious in interpreting this ensemble of early near-infrared measurements as indicative of large-scale flux variations. The observational complexities of working in the Orion region combined with a variety of aperture sizes may explain entirely the apparent differences in photometry.

## 5. SUMMARY

We have found photometric modulation in *H*- and *K*<sub>s</sub>-band light curves for BN consistent with periodic behavior. During 2000 March/April, the period was 8.28 days with a Lomb-Scargle FAP of less than 0.1%. The amplitude of the nearly sinusoidal light curve was  $\sim 0.2$  mag peak to peak (with an  $\sim 0.05$  mag

rms). The origin of the periodicity is not immediately obvious. Modulation of the light curve due to the rotation of inhomogeneities in either the photosphere or the inner circumstellar dust distribution is the least complicated model. Further multiwavelength photometric as well as emission-line profile monitoring can probe the period persistence, phase stability, and physical origins for the periodic behavior.

This publication made use of data products from 2MASS, which is funded by NASA and the NSF and is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center at Caltech. Science data and information services were provided by IRSA at IPAC. The authors would like to thank the 2MASS Observatory Staff and Data Management Team for acquiring and pipeline-processing the special survey observations used in this investigation. We thank Nick Scoville, Bill Herbst, Michael Meyer, and Roc Cutri for comments on drafts of this manuscript. We also thank Gerry Neugebauer for communicating previously unpublished data.

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